

Single-mode Semiconductor Reference Oscillator Development for Coherent Detection Optical Remote Sensing Applications

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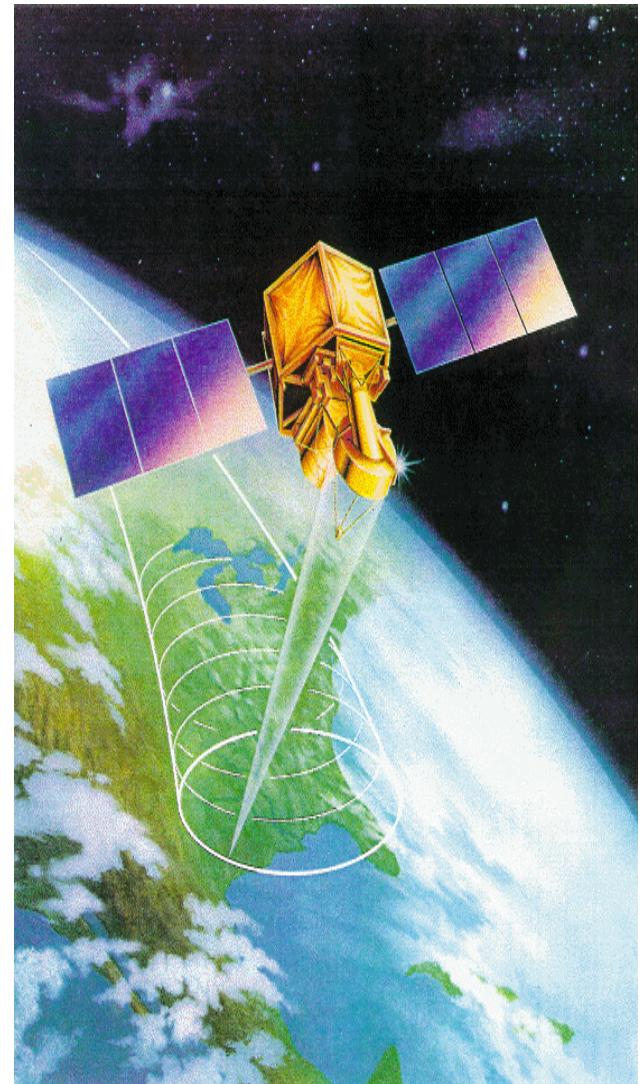
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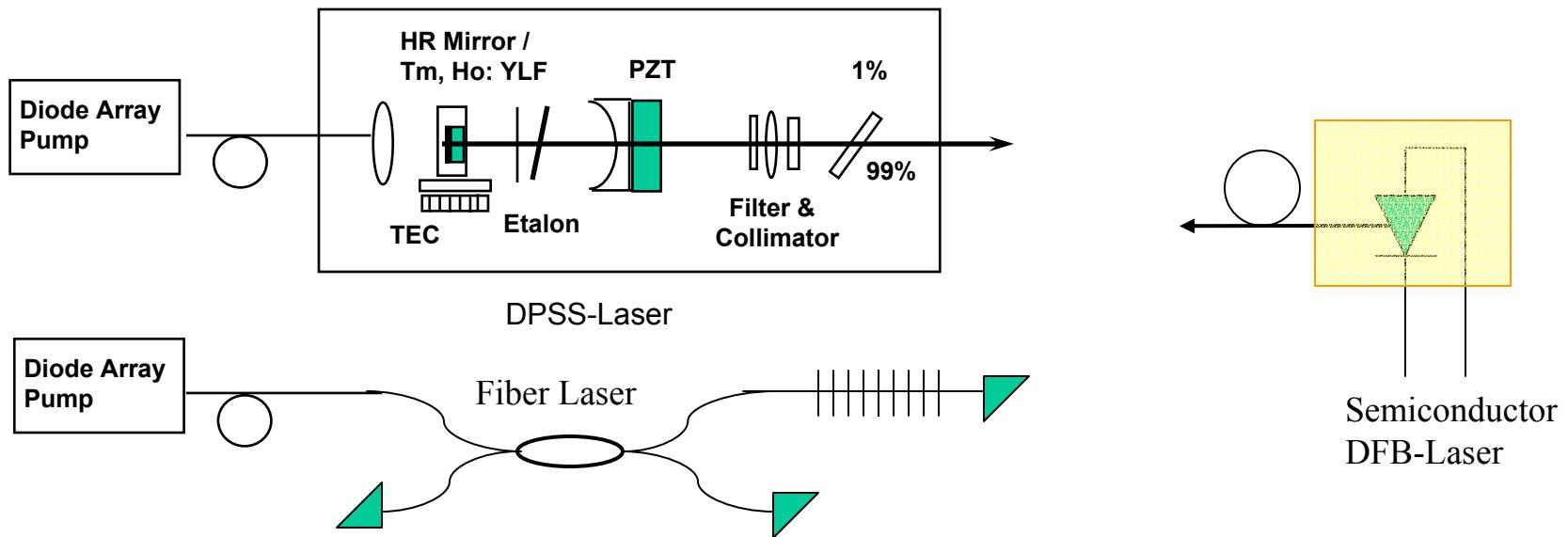
- Motivation
- Single mode narrow linewidth operation of semiconductor DFB lasers
- Corrugation pitch modulated (CPM) DFB Grating laser architecture
- Fabrication and testing of $1.55 \mu\text{m}$ and $2.05 \mu\text{m}$ CPM-DFB lasers in InP/InGaAs/InGaAsP compressively strained multi-quantum well structures.
- Hybrid Distributed Bragg Reflector GaSb/InGaAsSb/AlGaAsSb based lasers in $2.0 \mu\text{m}$ wavelength region and beyond.
- Summary

Space-Based Coherent Doppler Wind LIDAR

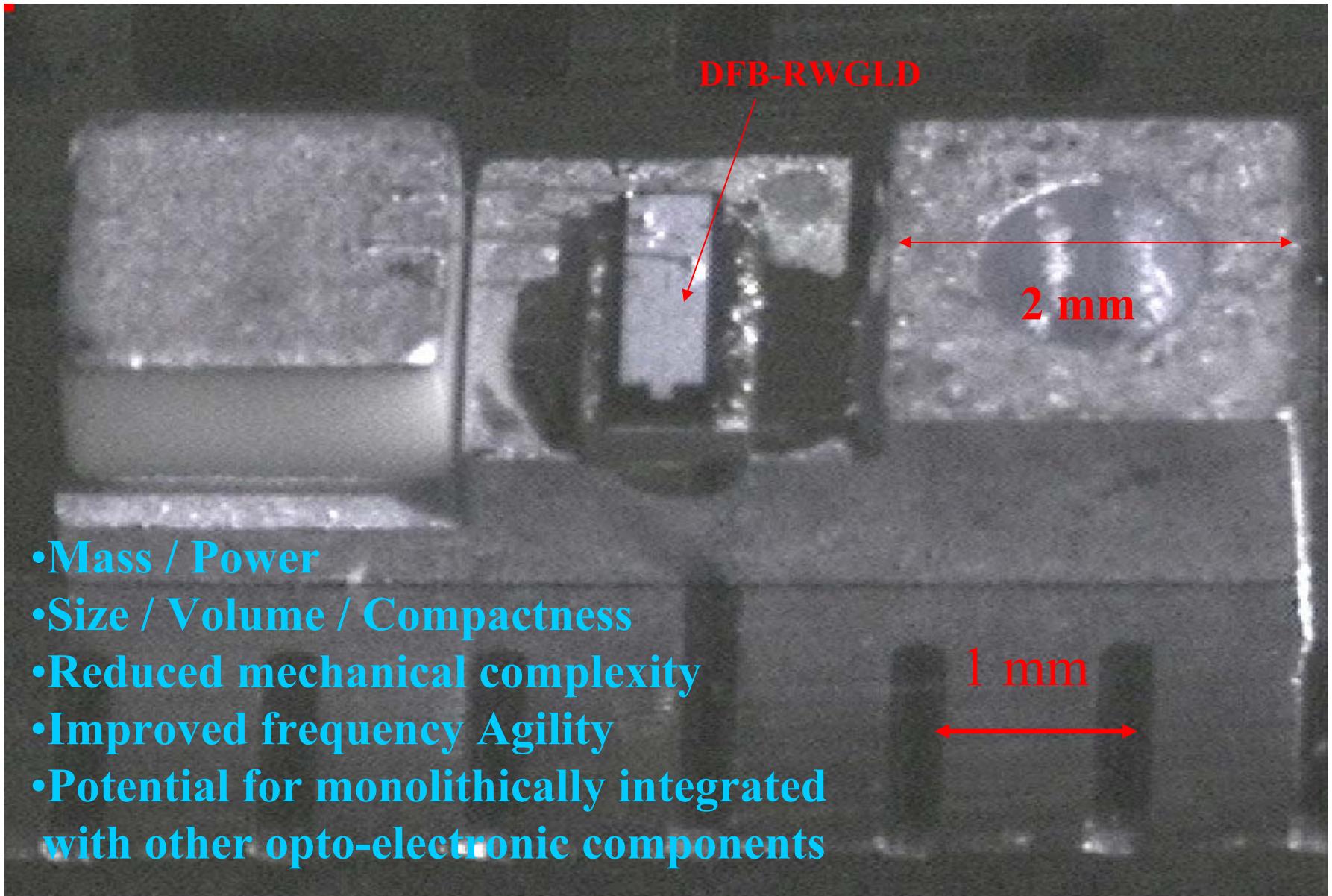
- Reliant on off-nadir beam scanning geometry
- Off-nadir scan pattern induces large platform-induced Doppler components which must be compensated by scan-synchronous tuning of a frequency-agile local oscillator (FALO) laser.
- Current diode pumped solid state FALO lasers are mechanically complex and relatively cumbersome, tuning stability and reproducibility are critically depends on maintenance of stringent alignment tolerances.
- Semiconductor FALO lasers are extremely attractive alternative to diode pump crystals.



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	Solid State	Fiber Laser	Semiconductor DFB-Laser
Linewidth	<10KHz	50-100 KHz	<100KHz
Tuning Range/Spectral Range	Few selected wavelengths Limited by gain material	Few Selected Wavelengths Limited by gain material	All Wavelengths from 0.6-2.1 μ m Electrical and Temperature Tuning
Power Consumption	Several Watts	~1 W (pump laser)	Low as .2 W
Mass	Kg	100g	1-10 g
Mechanical Stability	LOW Many components Optical alignment	Better Single Fiber Vibration Sensitive Strain tunes laser	Best Monolithic



linewidth Broadening Consideration

Linewidth rebroadening at relatively low optical power levels limits the use of single -mode Distributed Bragg Reflector (DBR) standard Distributed Feedback (DFB) laser architectures as FALO devices.

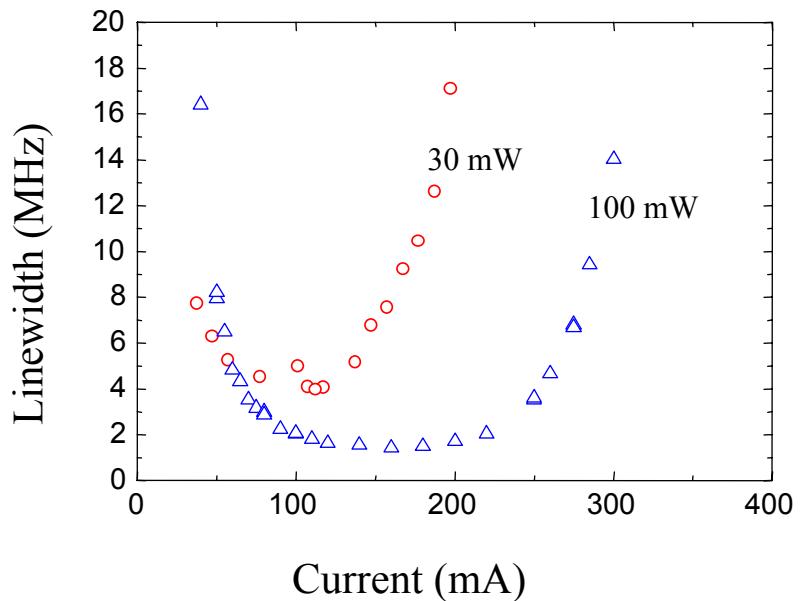
Gain non-linearities cause a non-uniform refractive index change along the laser cavity that lead to power dependent, single mode instability and linewidth rebroadening.

Spectral linewidth of a semiconductor DFB laser:

$$\Delta\nu = \frac{\hbar\omega n_{sp}}{P} (1 + \alpha^2) + \nu_{RB} \left(\frac{P}{P_{NL}} \right)$$

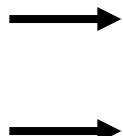
Modified Schawlow-Townes term.
Decrease linewidth with power.

Nonlinearities rebroaden
the linewidth at high
power



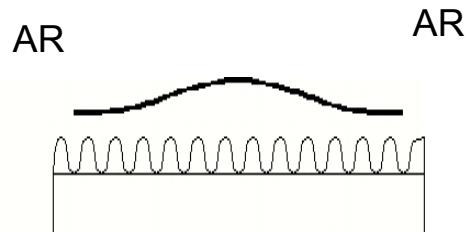
Way to achieve
sub-100kHz
linewidth

1. Avoid rebroadening
2. Achieve high power operation.



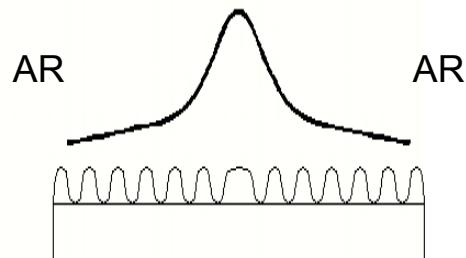
Control intracavity power
To suppress spatial hole burning effect.

Minimize losses,
increase efficiency

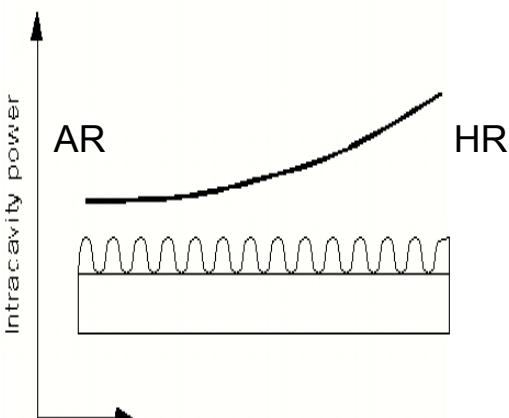


Uniform Grating DFB (AR/AR)

- Two degenerate modes
- Relatively flat longitudinal intensity

 $\Delta/4$ DFB (AR/AR)

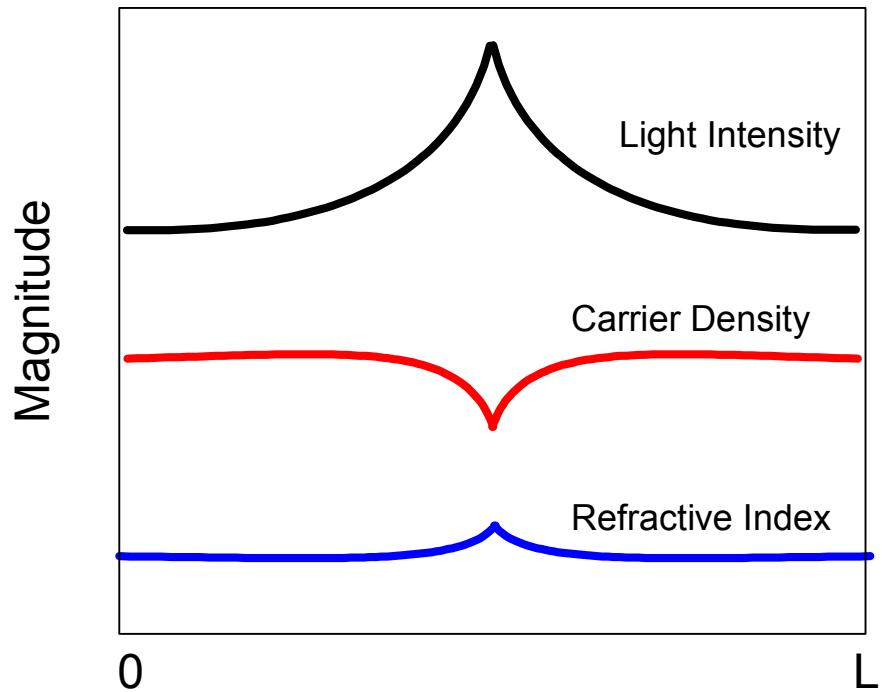
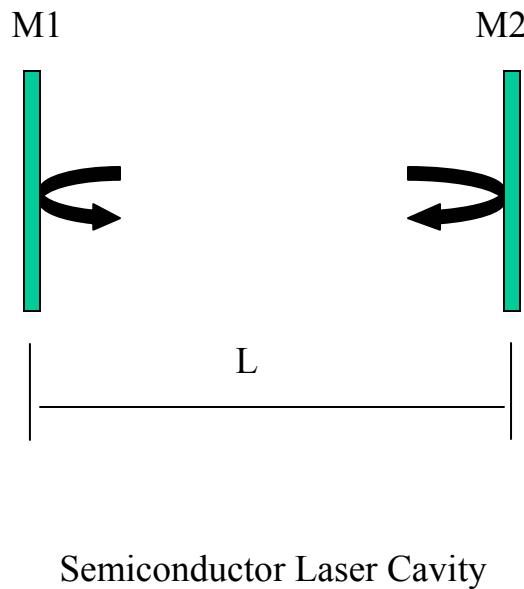
- Central mode in stop band
- Good SMSR
- Intensity peaks in center of cavity, spatial hole burning at high power.



Uniform grating DFB (AR/HR)

- Facet reflection puts mode in stop band
- Pick devices with $\Delta/4$ phase shift for good SMSR
- Intensity peaks at facet - spatial hole burning

Spatial Hole Burning

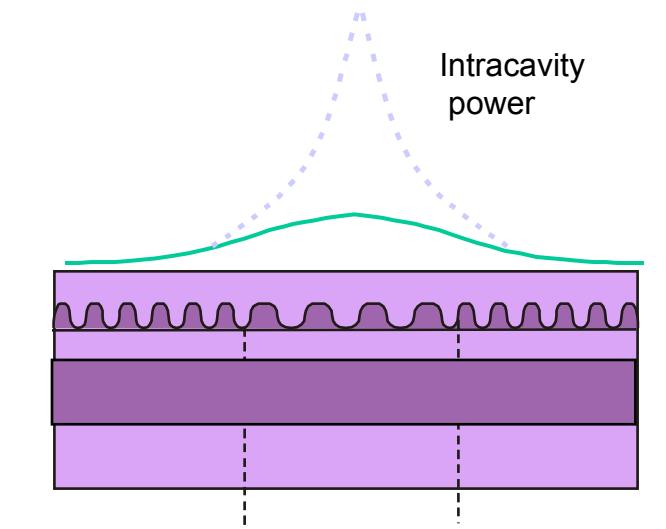


Light intensity ↑ → Carrier density ↓ → Plasma effect → Refractive index ↑

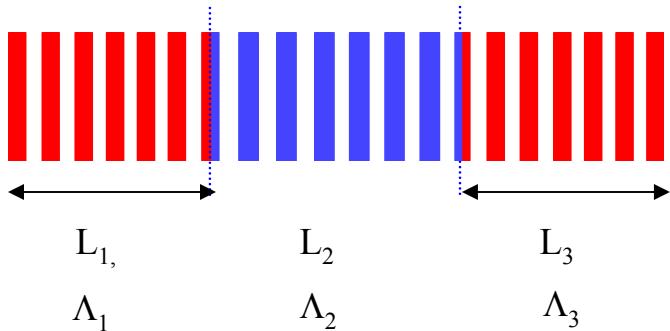
Spatial Hole Burning

$$\begin{aligned} n_{\text{eff}}(z) &= n_{\text{eff}0}(z) + \Delta n_{\text{eff}}(z) \\ &= n_{\text{eff}0}(z) + \Gamma_w \cdot \frac{dn}{dN} \cdot (N(z) - N_{\text{th}}) \end{aligned}$$

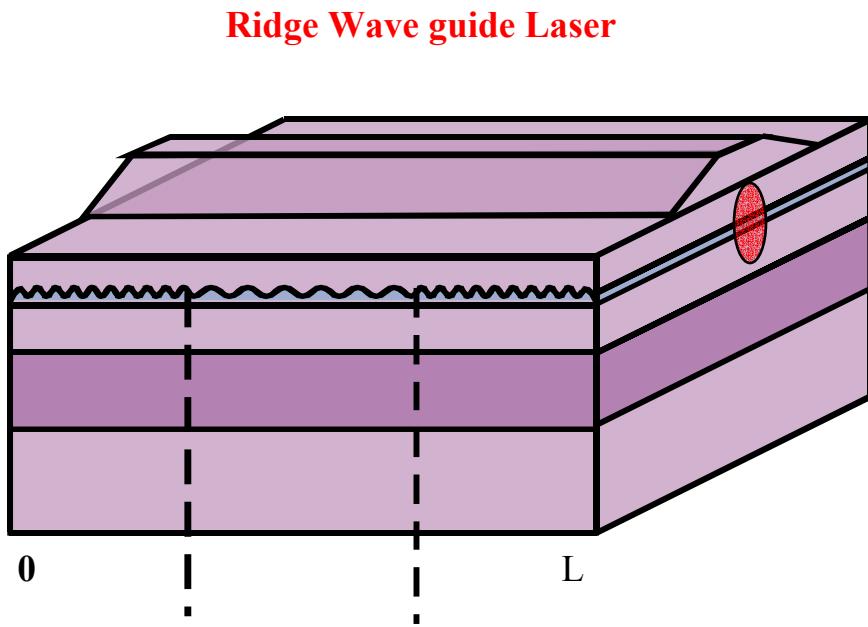
$$\alpha = \frac{4\pi}{\lambda} \frac{\frac{dn}{dN}}{\frac{dg}{dN}}$$



Phase arranging section



$$\Lambda_2 = (N+1/2)/N^* \Lambda_{1,3}, \text{ where } N = L_{1,3}/\Lambda_{1,3}$$



Phase arranging section

$$L_2 = L_1 + \Lambda_1/2$$

e.g., for $\lambda=2.05 \mu\text{m}$
 cavity length = $1500 \mu\text{m}$
 $L_1 = L_3 = 500 \mu\text{m}$
 $L_2 = 500 \mu\text{m} + 160\text{nm}!!!$

Detuning center region of Distributed Feedback grating keeps intra-cavity power uniform along the laser cavity and avoids linewidth broadening at high powers.

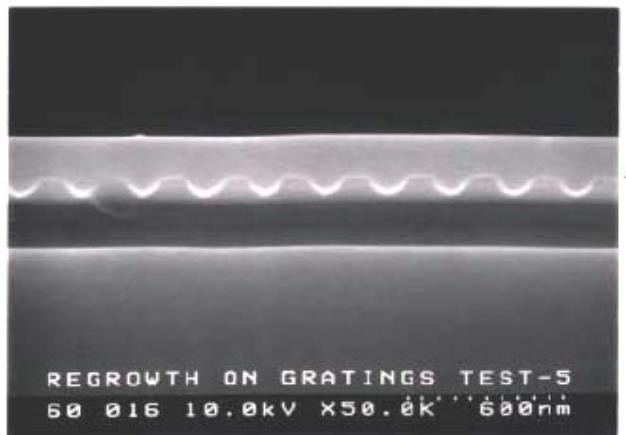
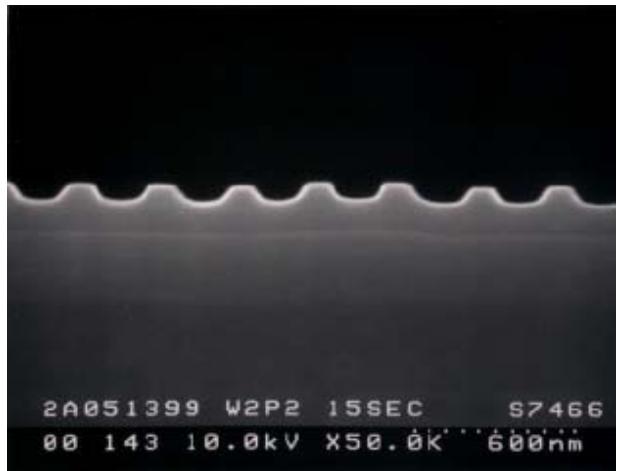
E-beam lithography System



JEOL JBX-9300FS



[Grating-Structure -Uniform - CPM, \$\lambda/4\$](#)
[Grating + or - detuning](#)



Grating Etch and Overgrowth
- planarization
- defect propagation

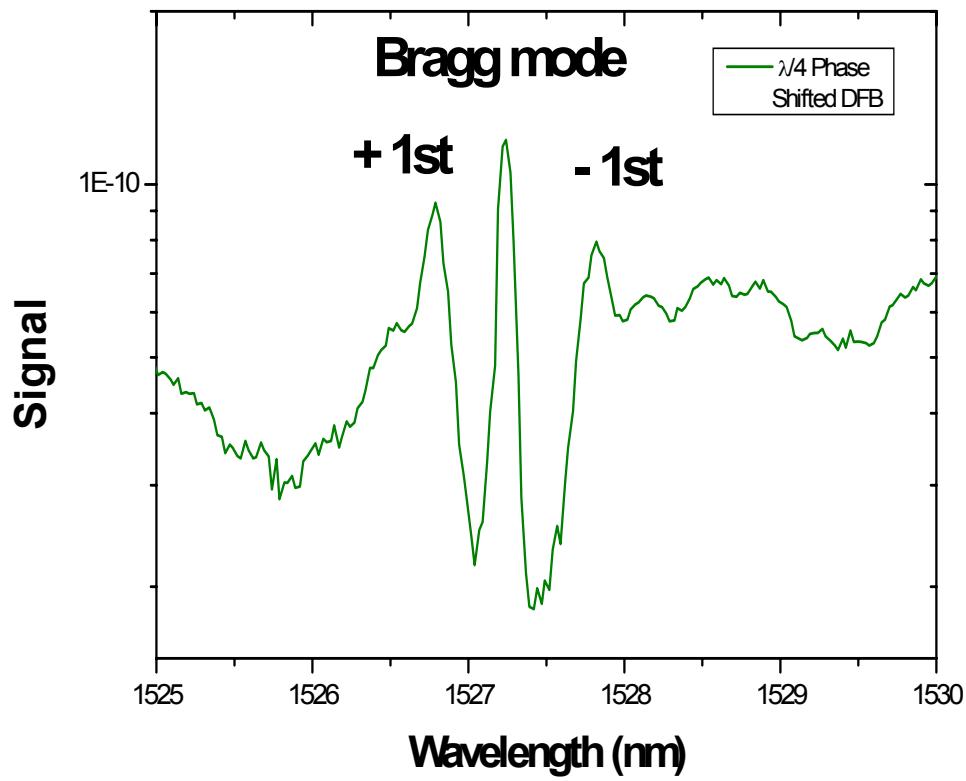
- *Wavelength*
 - 2.05 μm to match eye-safe Tm,Ho:YLF transmitter technology under development for atmospheric window region
- *Linewidth*
 - <500 kHz to address 1-m/s velocity resolution requirement
- *Tunability*
 - >10 GHz to compensate for platform-induced Doppler on orbit
- *Power*
 - ~40 mW to ensure shot-noise limited heterodyne receiver operation

Implementation Approach



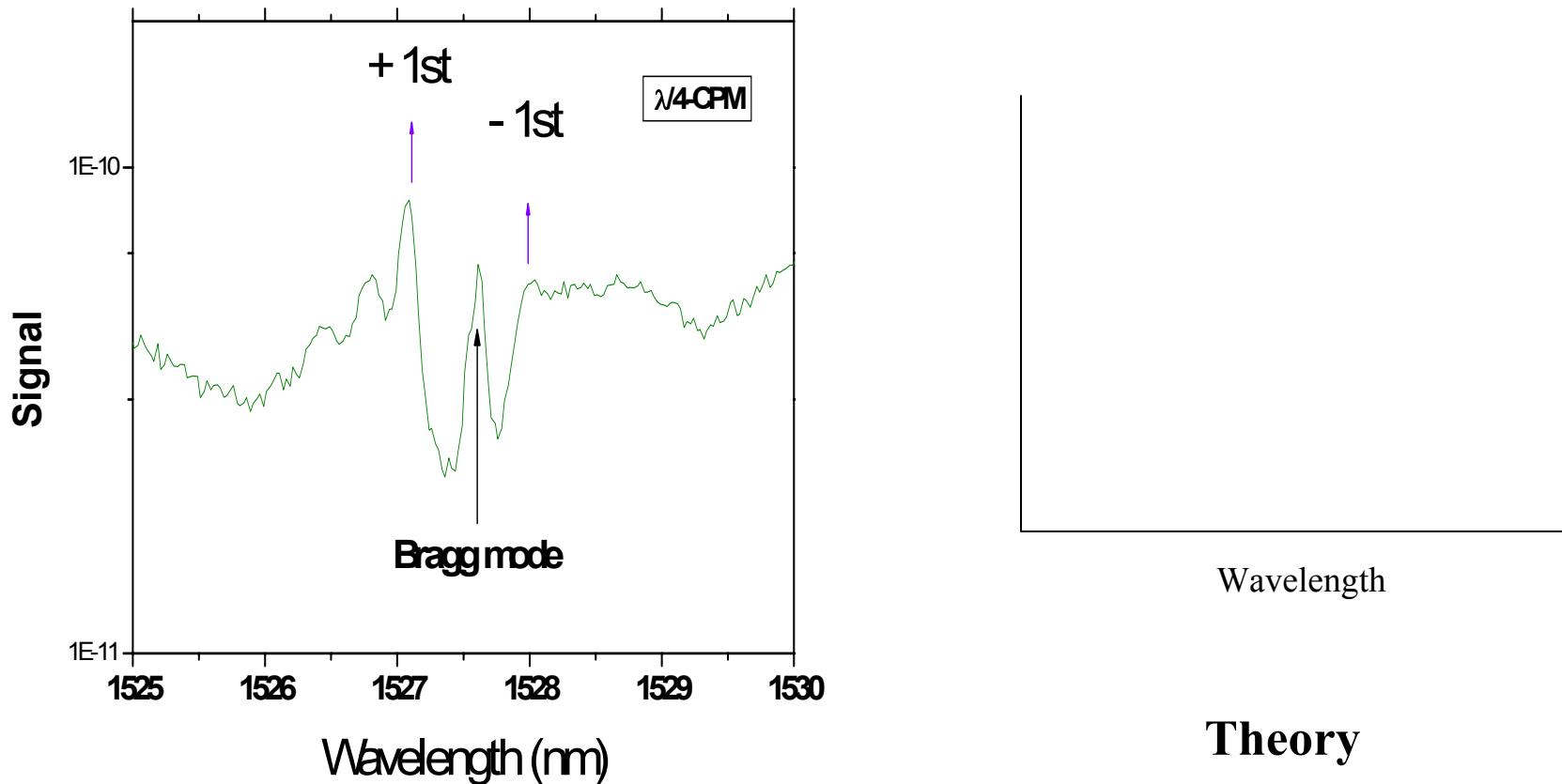
Laser technology development in the **1.5-1.6 μm** and **2.05-2.065 μm** wavelength range has followed parallel paths:

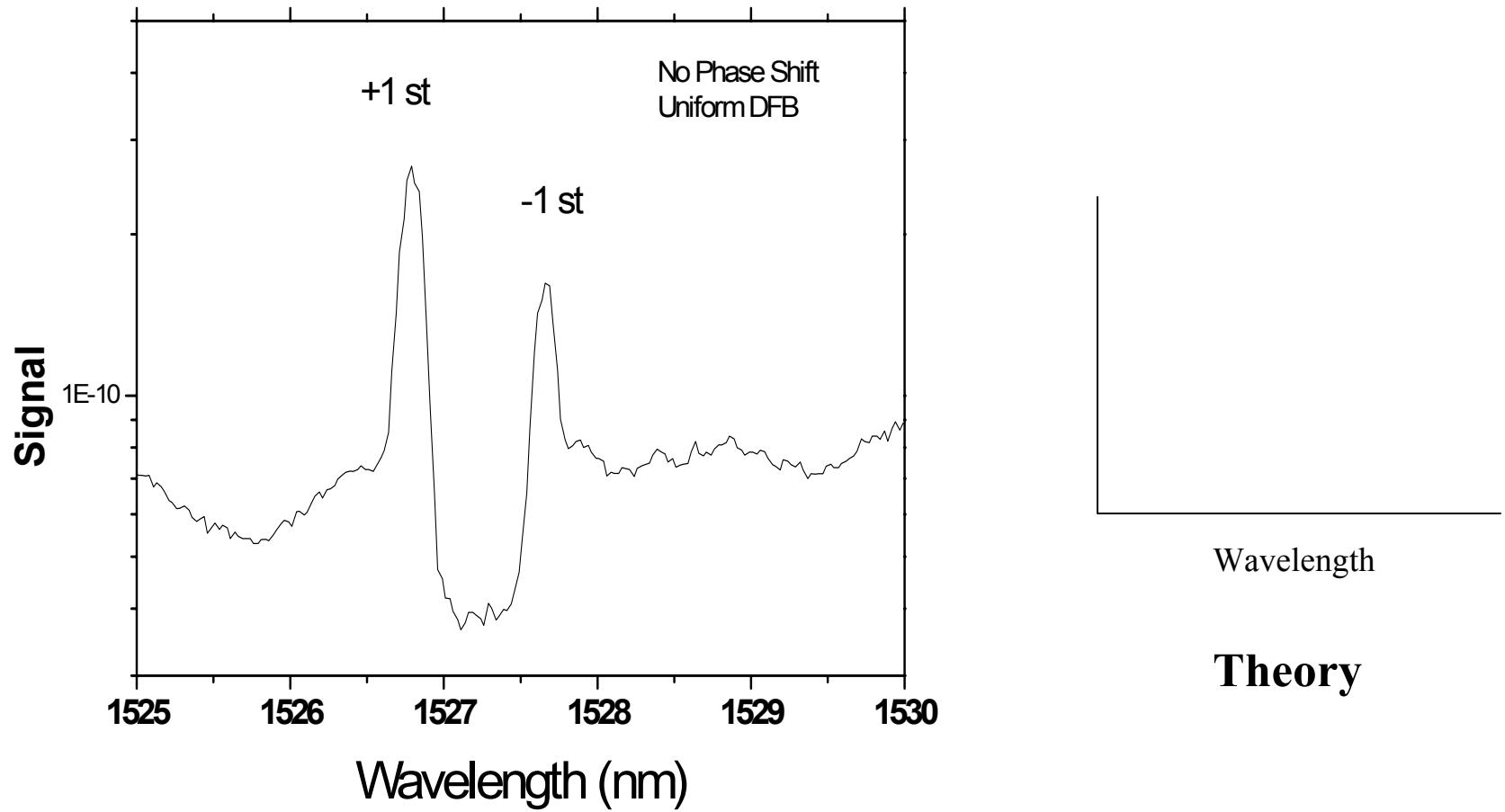
- **Corrugated pitch modulated DFB architecture in InGaAs/InGaAsP/InP compressively strained multi-quantum well structures at 1.5-1.6 μm and 2.05-2.65 μm wavelength range.**
- **External Distributed Bragg grating reflector (DBR) architecture in InGaAsSb/AlInGaSb/GaSb multi-quantum well structures at 2.05-2.65 μm and longer wavelength range.**

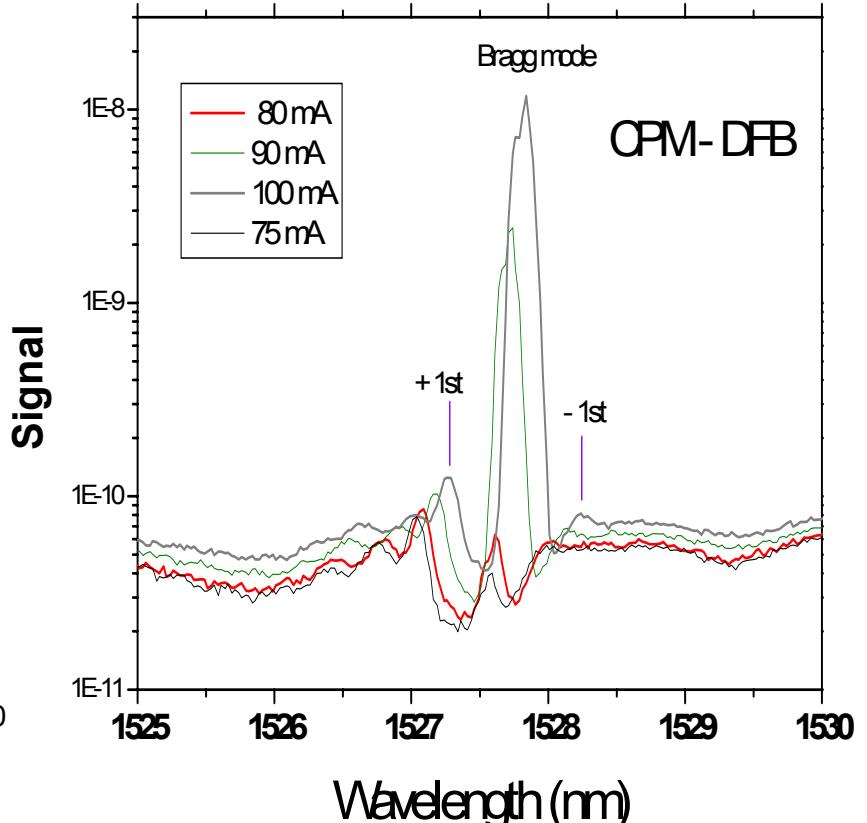
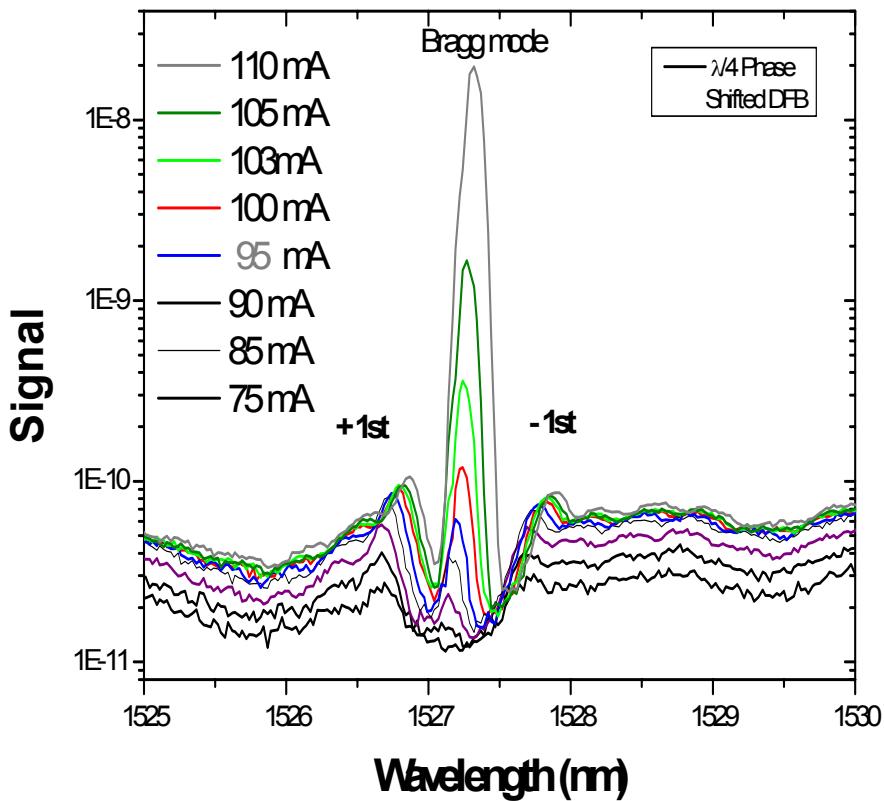
Measured Optical Spectrum at $1.3\lambda I_{\text{th}}$ 

Wavelength

Theory

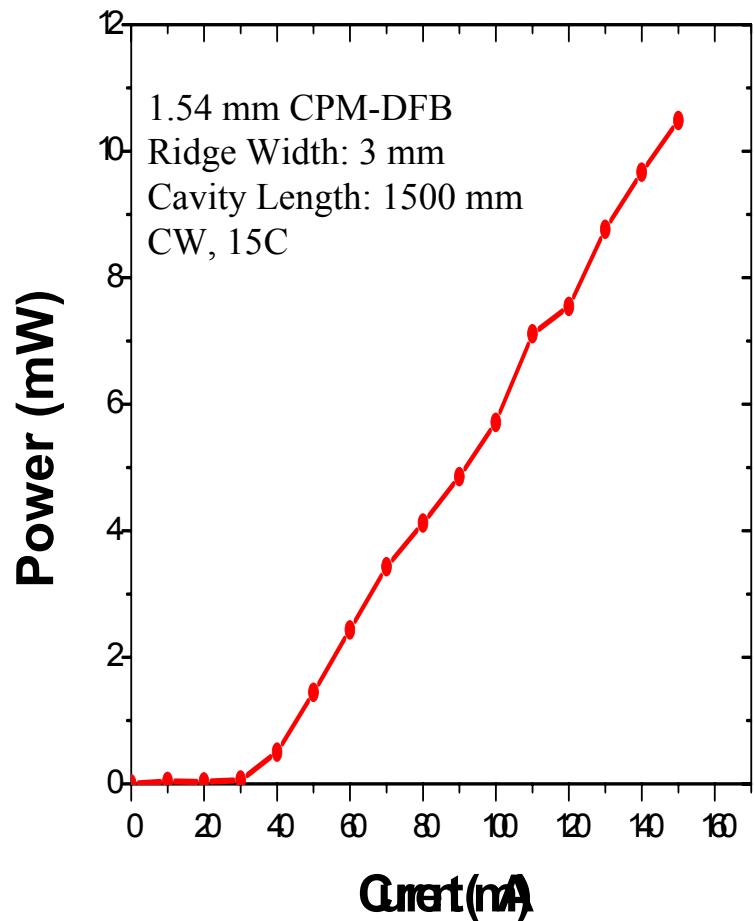
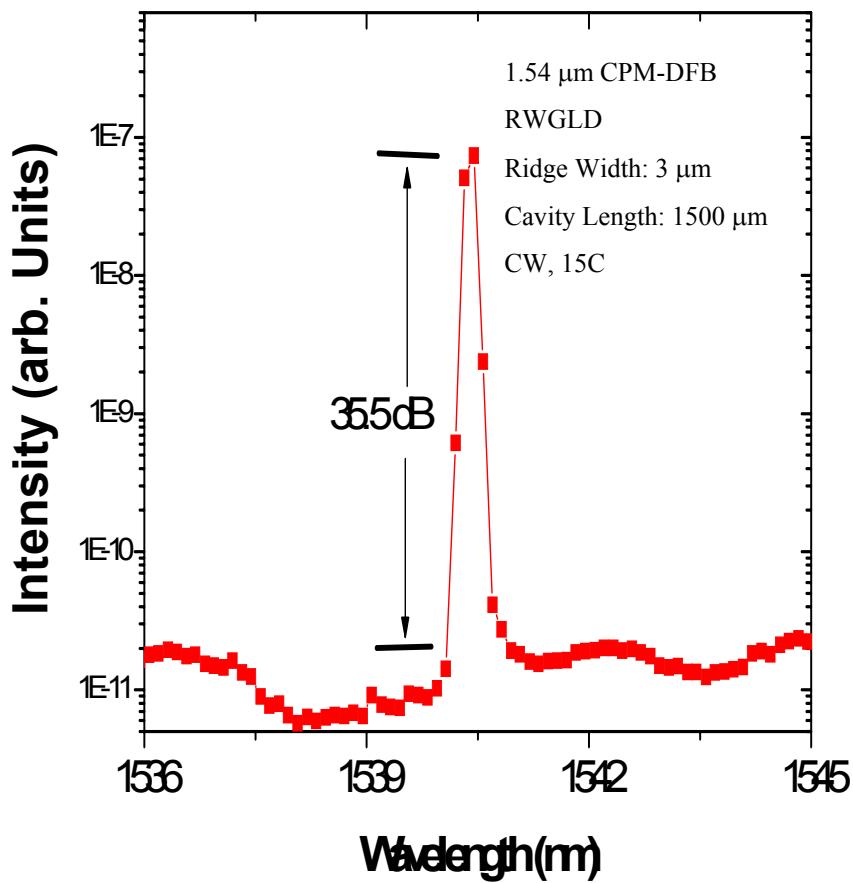
Measured Optical Spectrum at $1.2X\text{I}_{\text{th}}$ 

Measured Optical Spectrum at 1.2XI_{th}

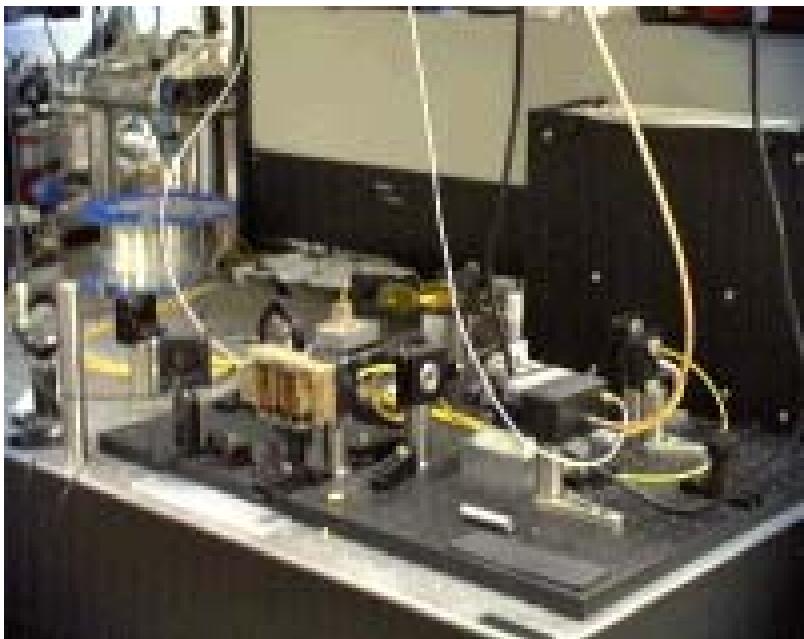
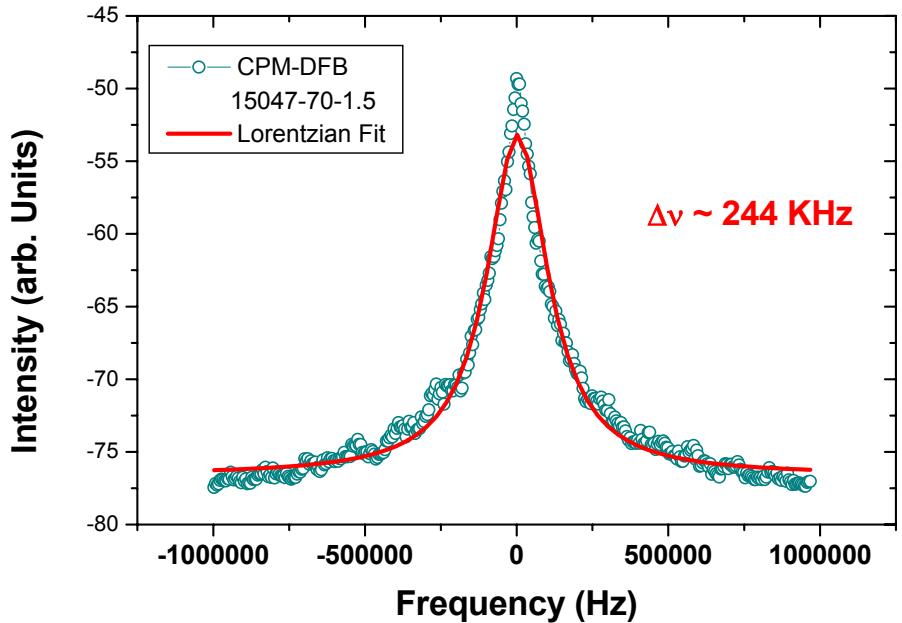


Current Tuning: $\sim 0.1 \text{ \AA / mA}$
 $\sim 1.3 \text{ GHz / mA}$

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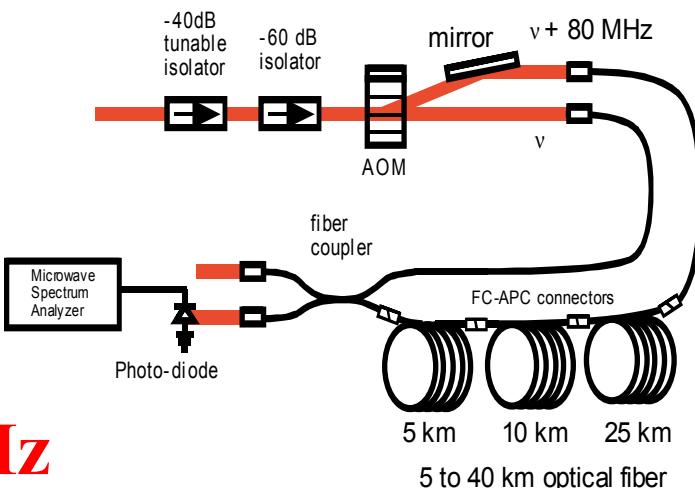


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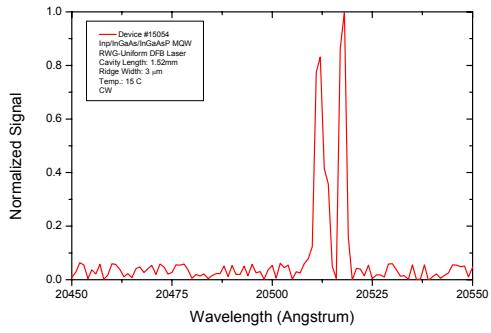
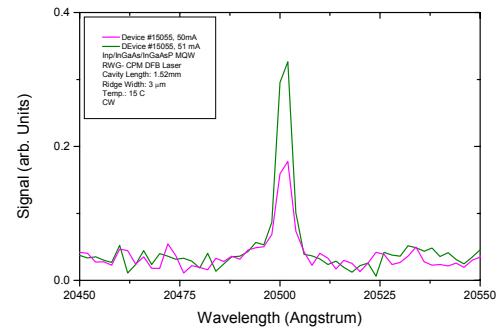
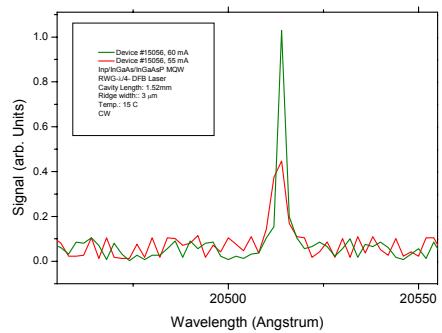
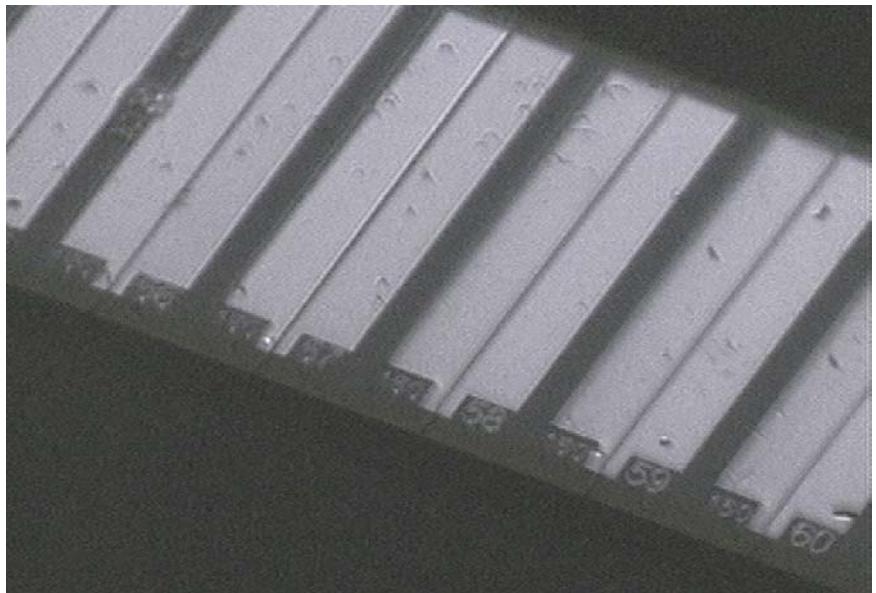
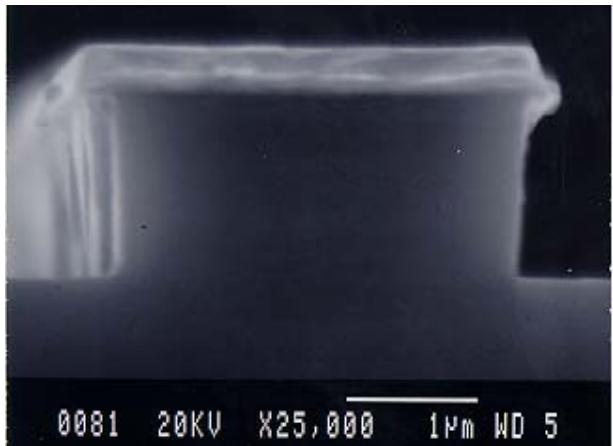


Beat note spectrum of a corrugation pitch modulated (CPM)-DFB laser using Delayed Self-Heterodyne System

Linewidth (FWHM) ~ 244 kHz



2.05 μm , different DFB laser architectures fabricated adjacent to each other on the same bar

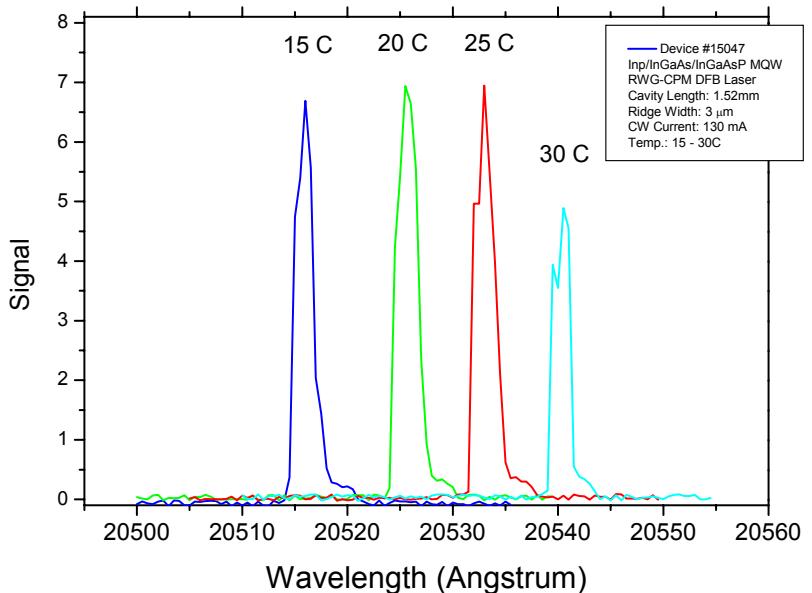
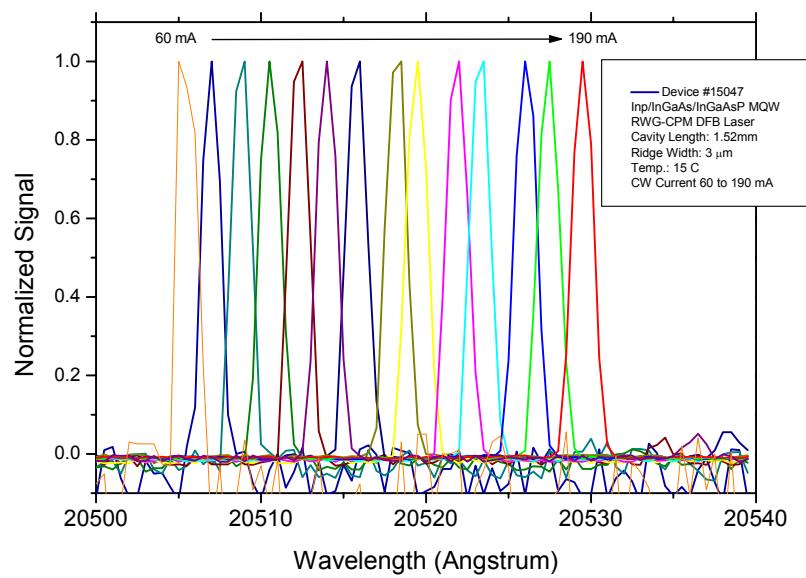


$\lambda/4$ -DFB

CPM-DFB

Uniform DFB

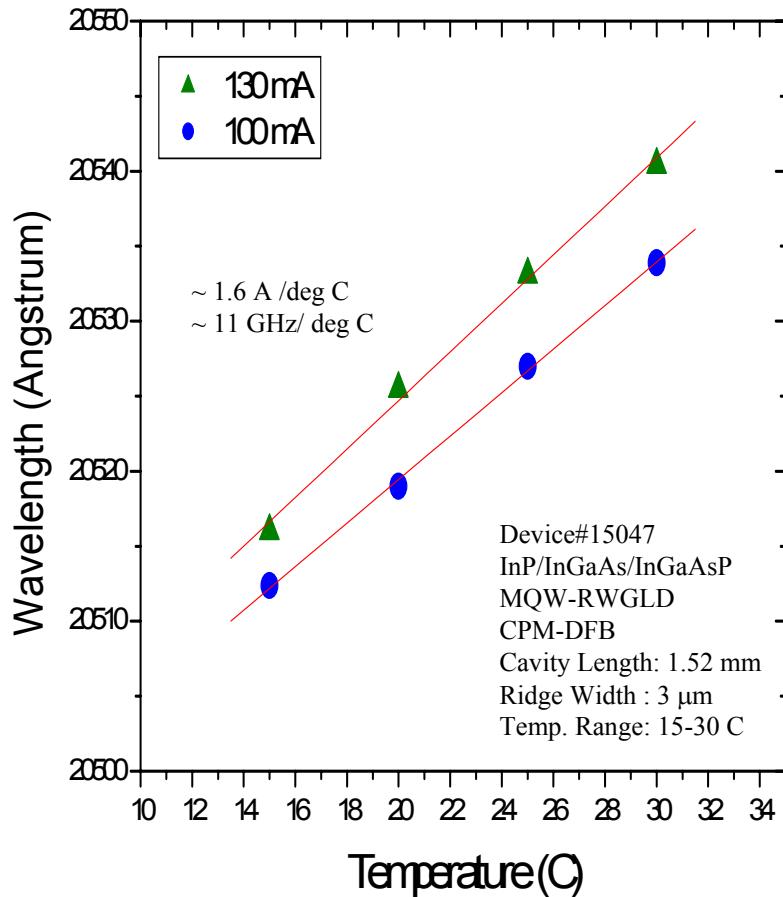
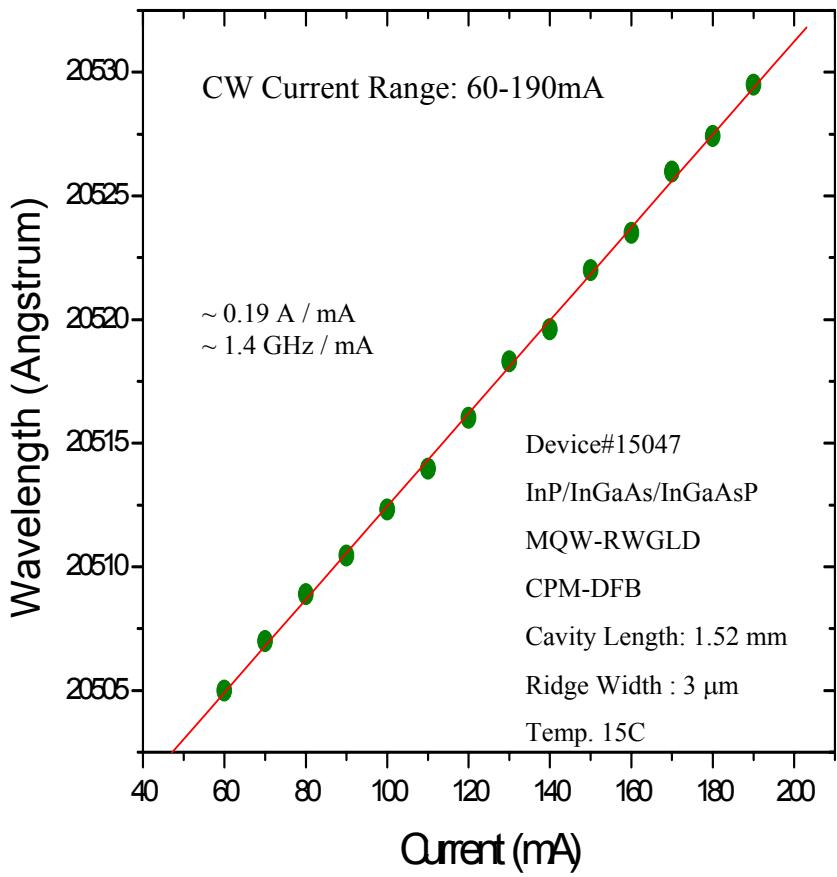
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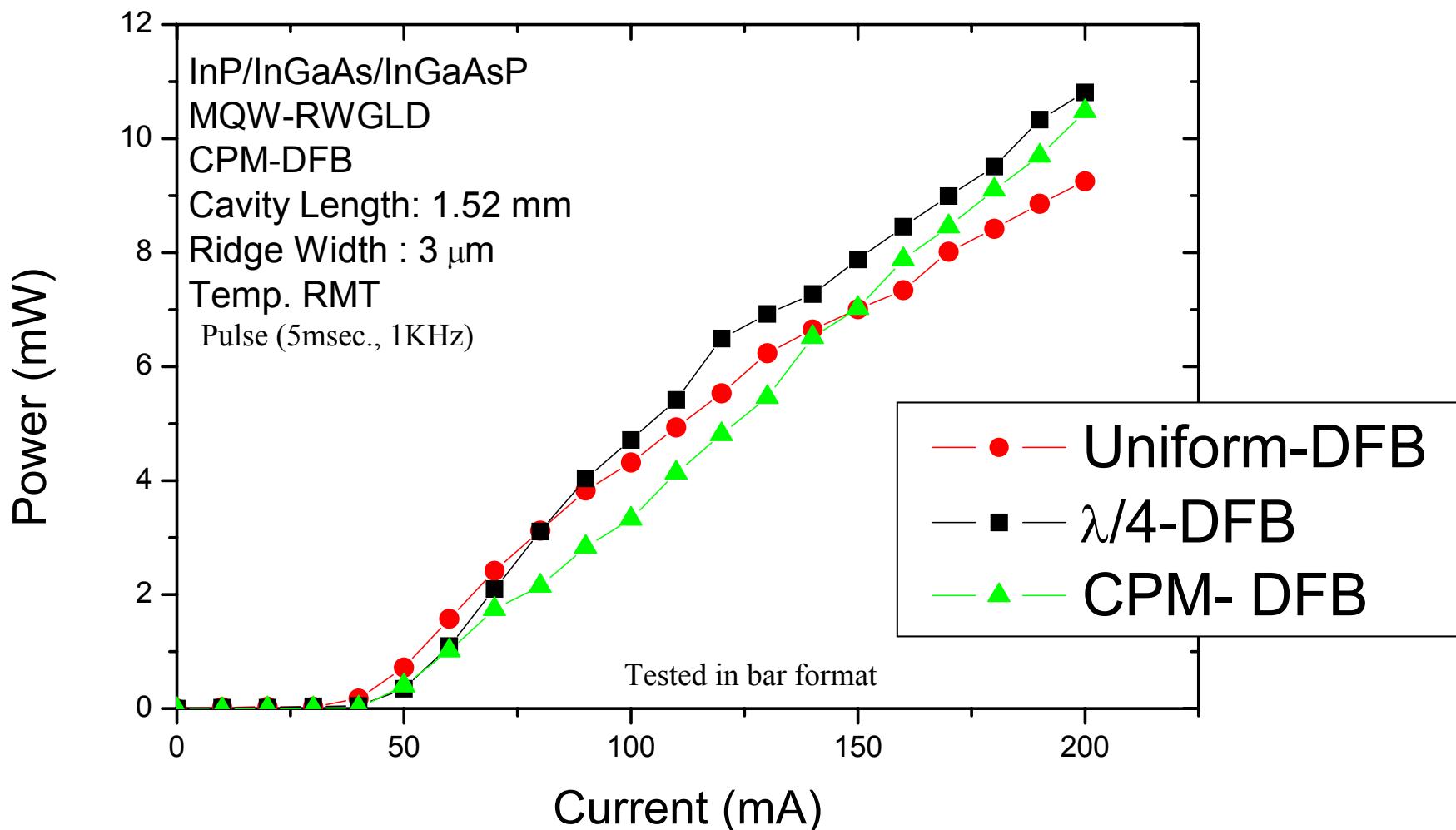
Current Tuning

Temperature Tuning

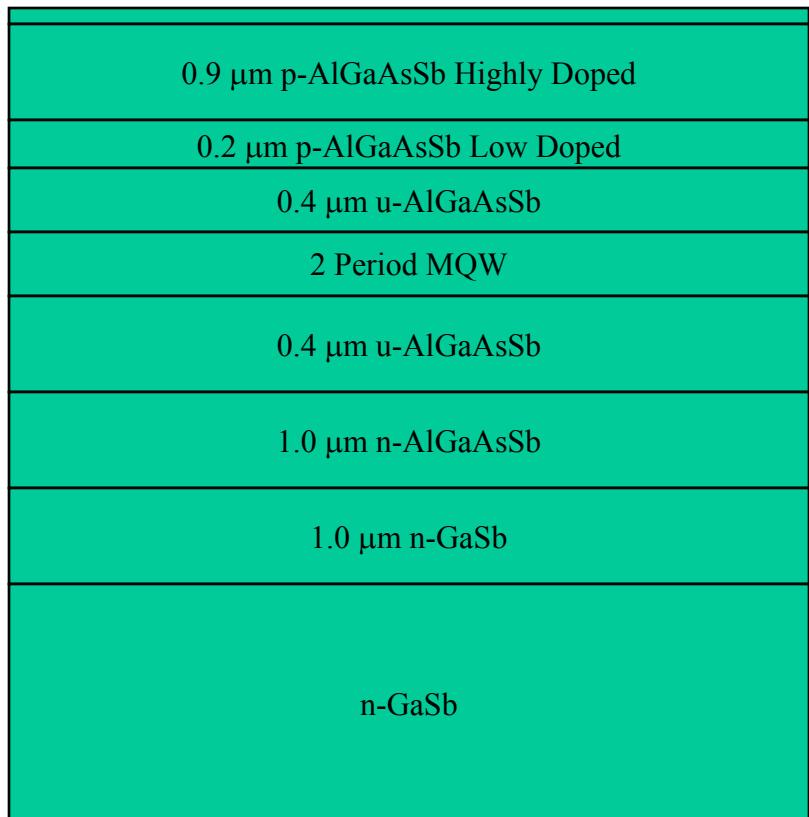
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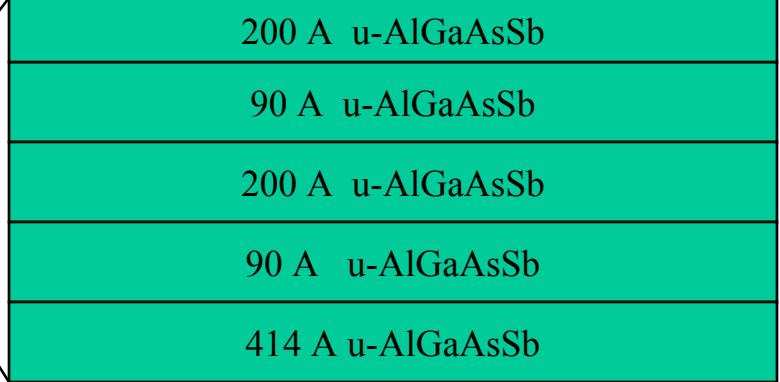
DFB lasers with CPM, $\lambda/4$ -DFB and Uniform Grating Structures fabricated adjacent to each other at $2.05\text{ }\mu\text{m}$
On the same wafer bar.



Cross-Section Schematic



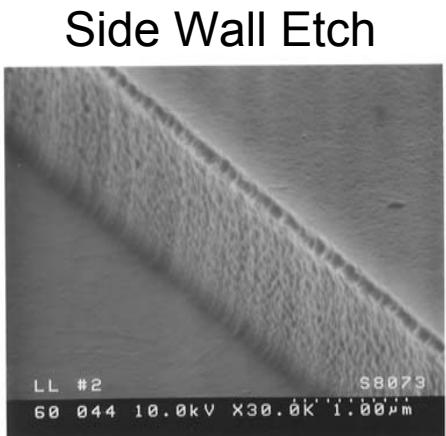
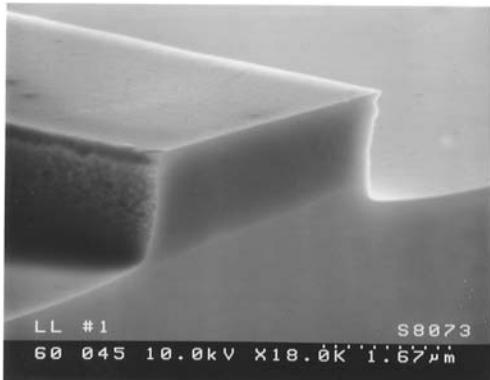
2-Period MQW Structure



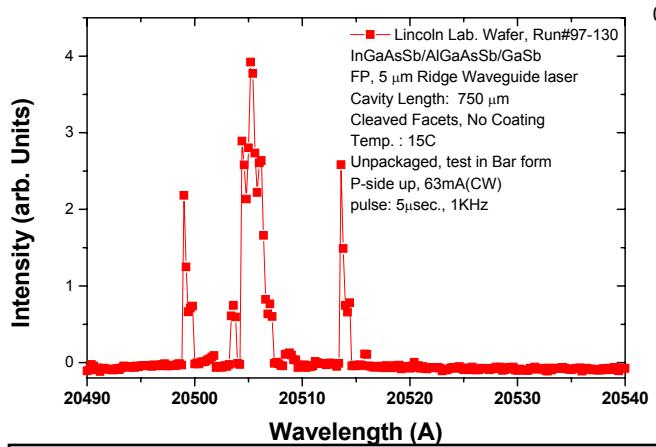
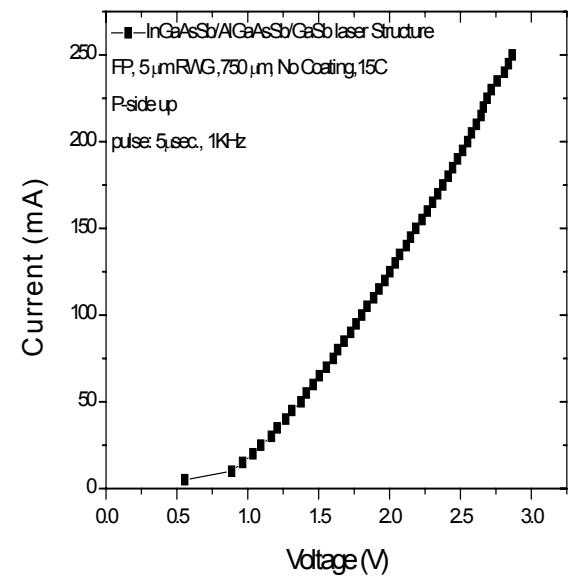
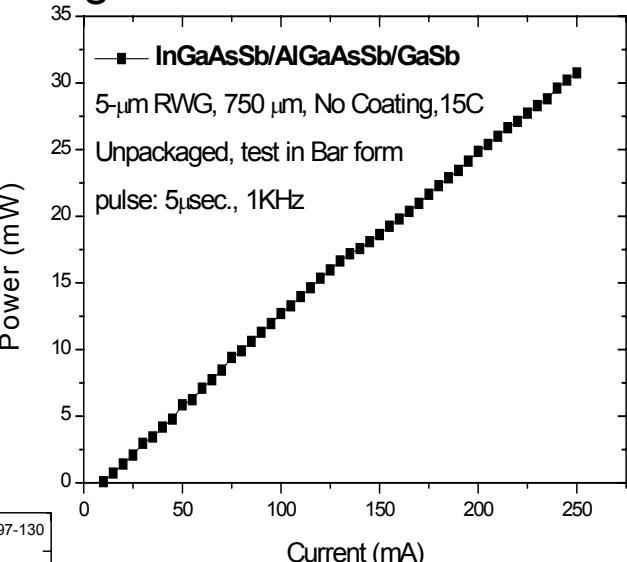
*MIT Lincoln Lab. collaborating
at no cost to produce test wafers
based on this design*

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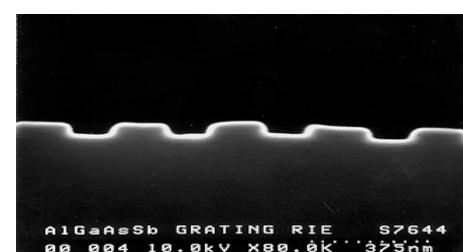
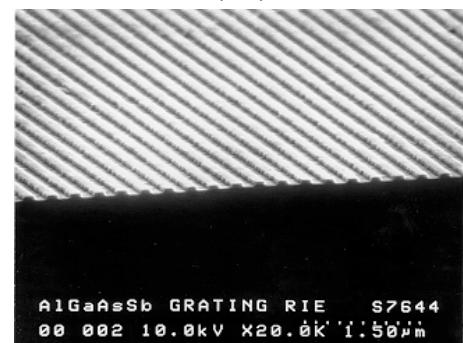
Ridge Waveguide Profile



Light-Current Characteristic

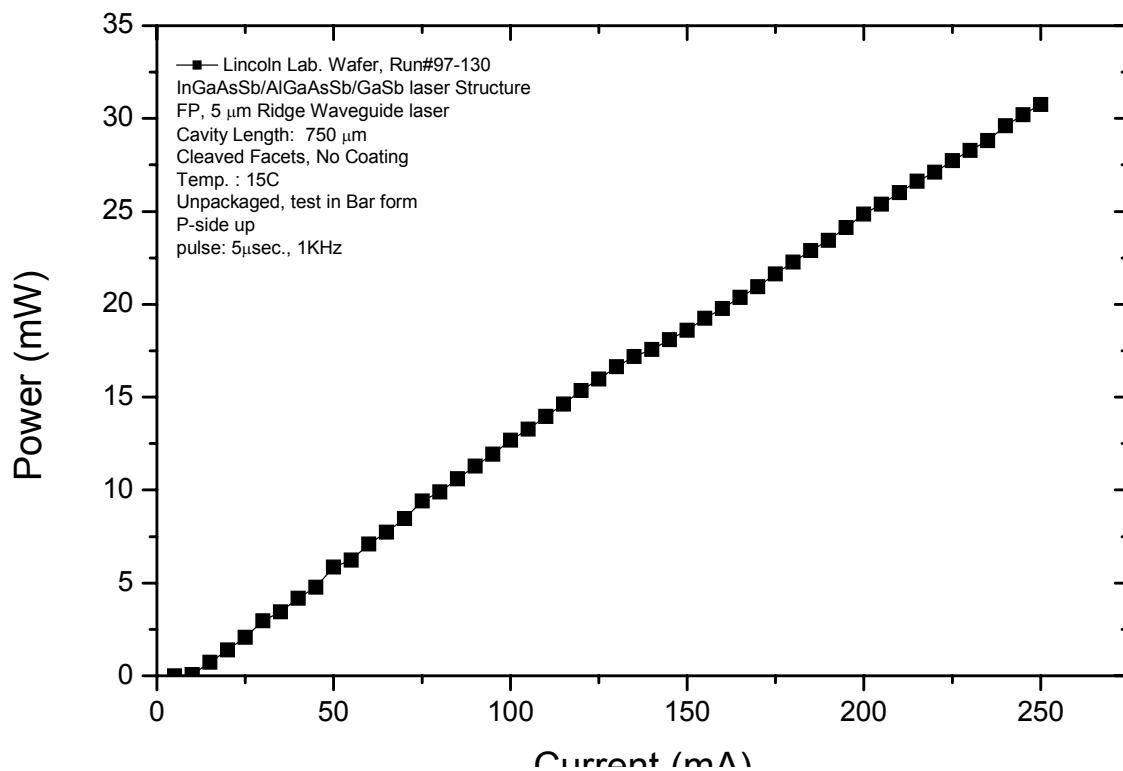


Optical Spectral Characteristics of
InGaAsSb/AlGaAsSb/GaSb Fabry-
Pérot 5- μ m Ridge Waveguide Laser

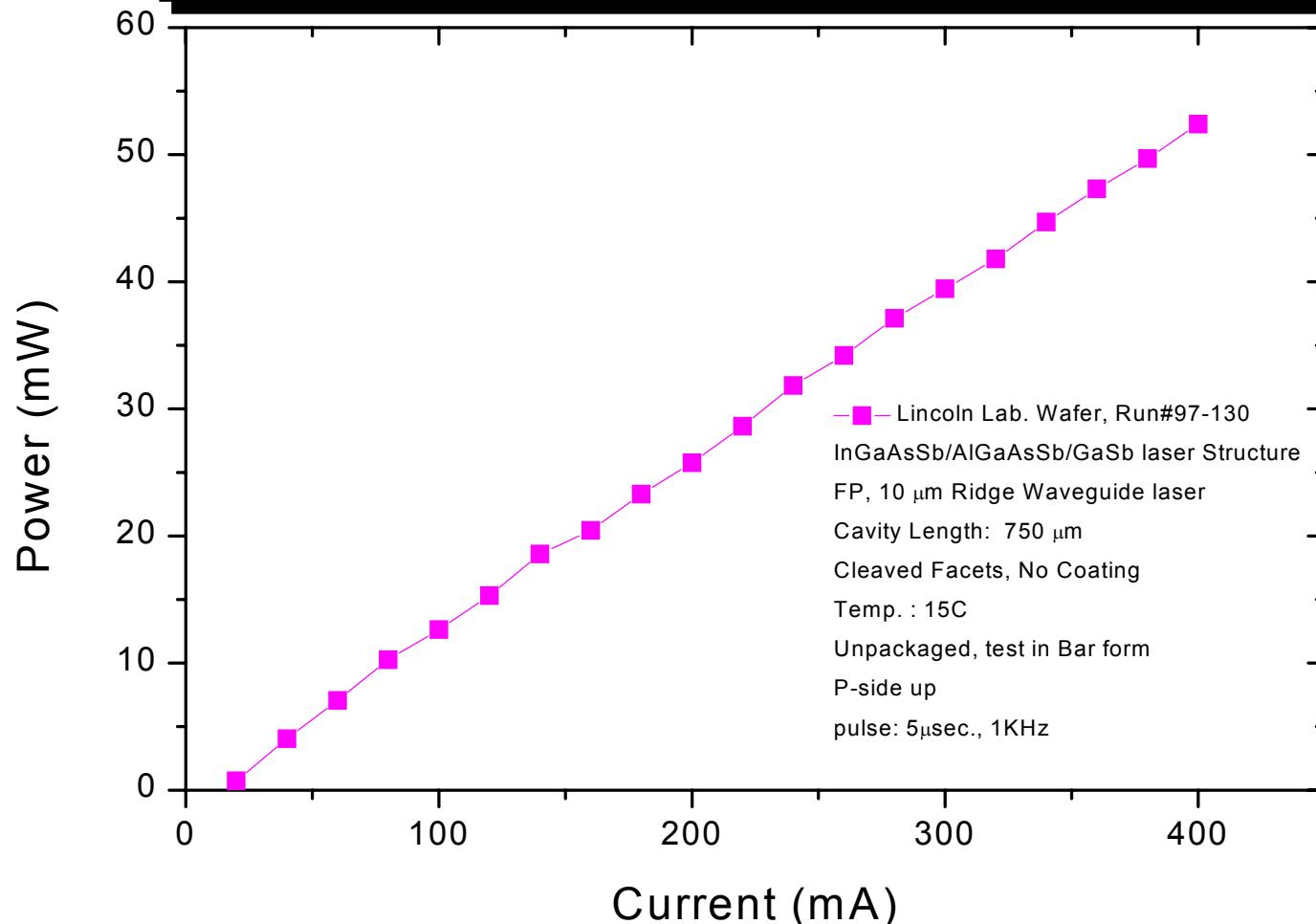


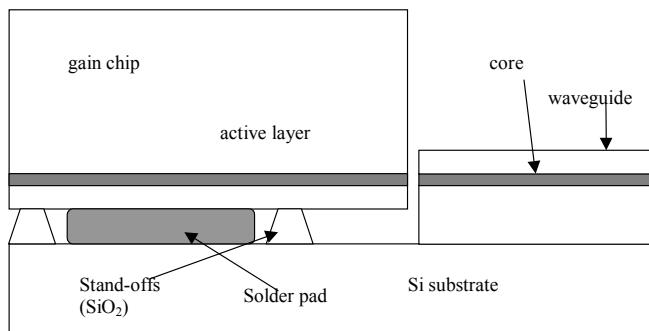
I-V Characteristic

Pulsed L-I Characteristics of InGaAsSb/AlGaAsSb/GaSb
Fabry Perot 5 μm Ridge Waveguide Laser

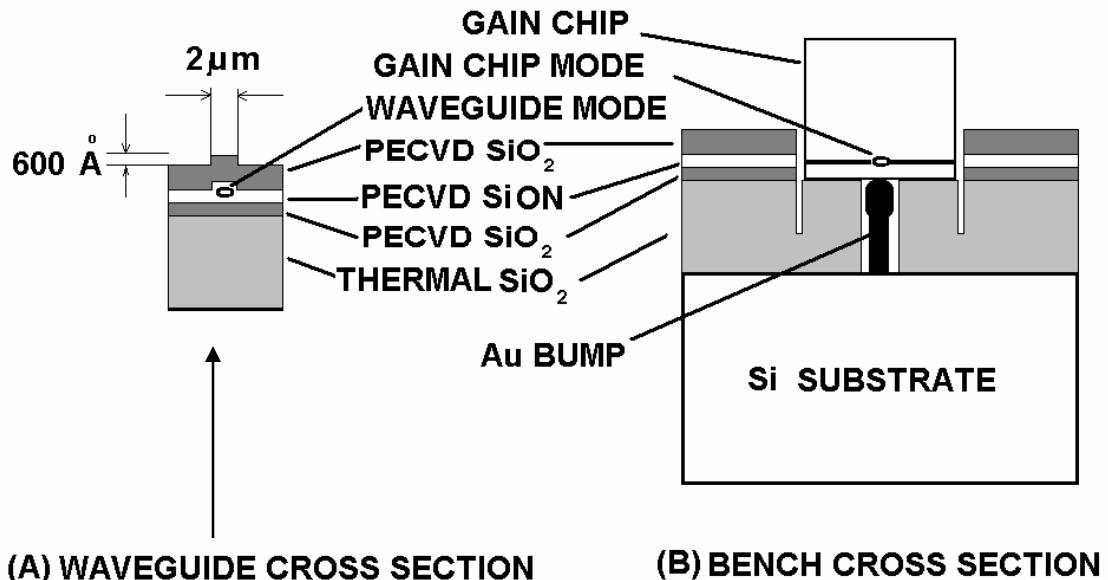


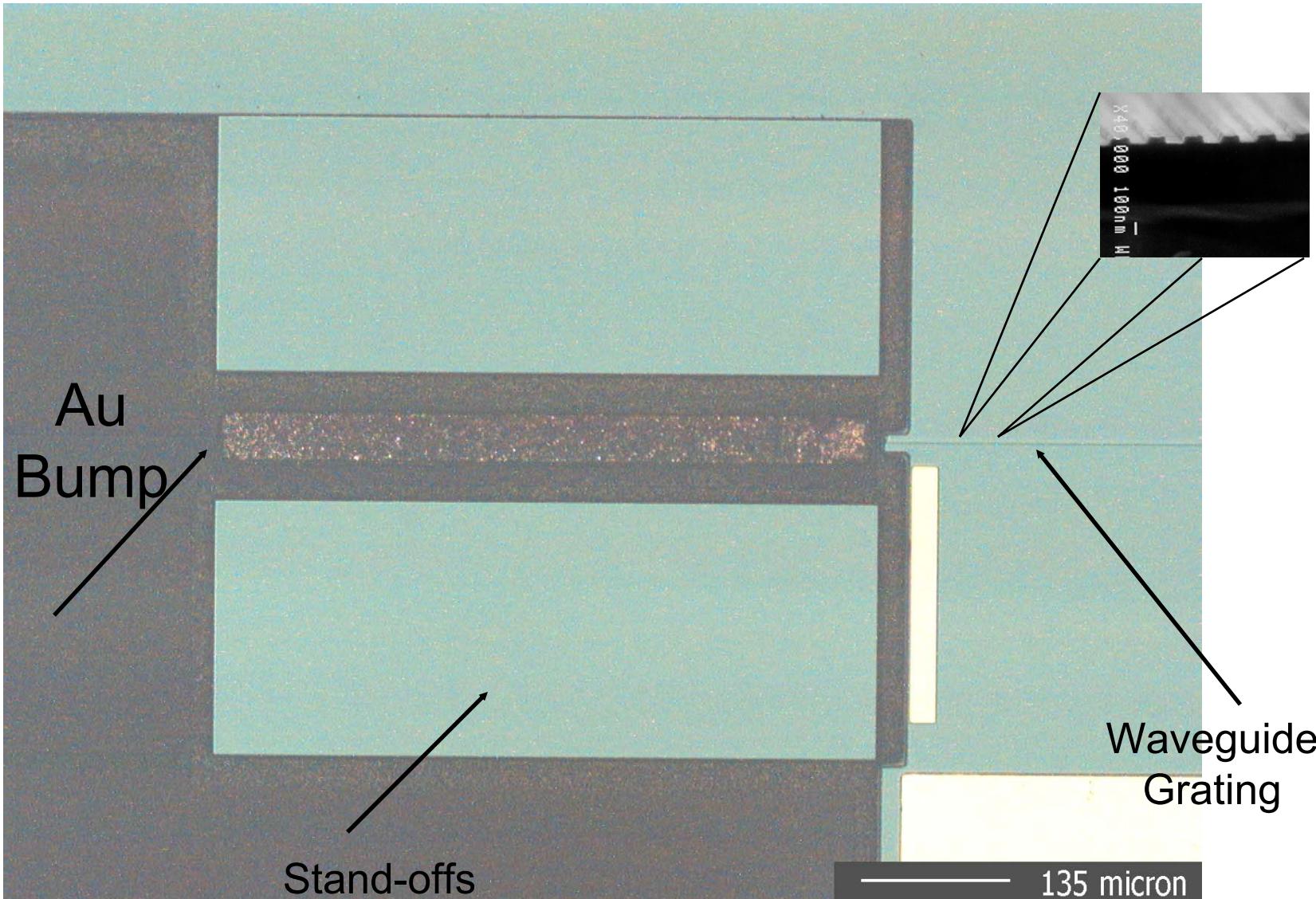
Pulsed L-I Characteristics of InGaAsSb/AlGaAsSb/GaSb
Fabry Perot 10 μm Ridge Waveguide Laser





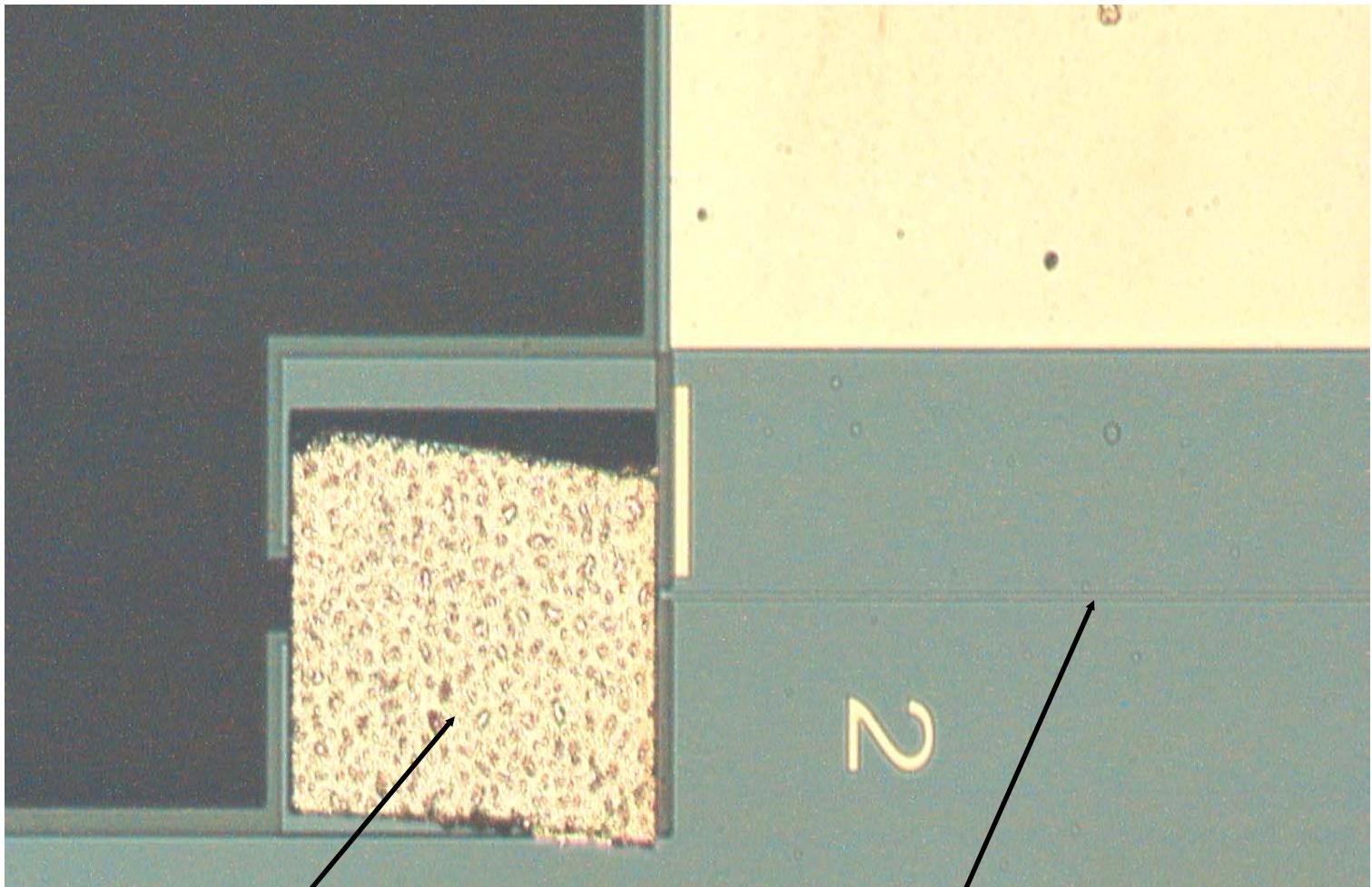
Vertical Alignment using Terraced Substrate





(SiO₂) for P-side flip-chip

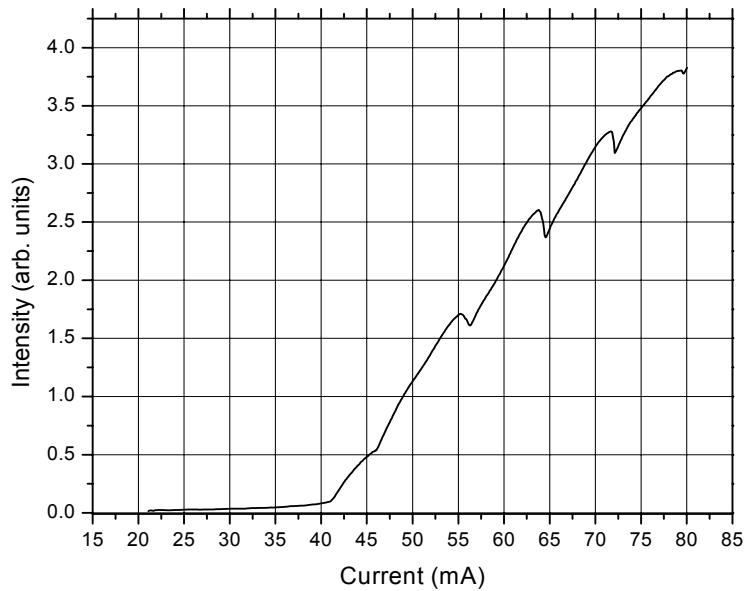
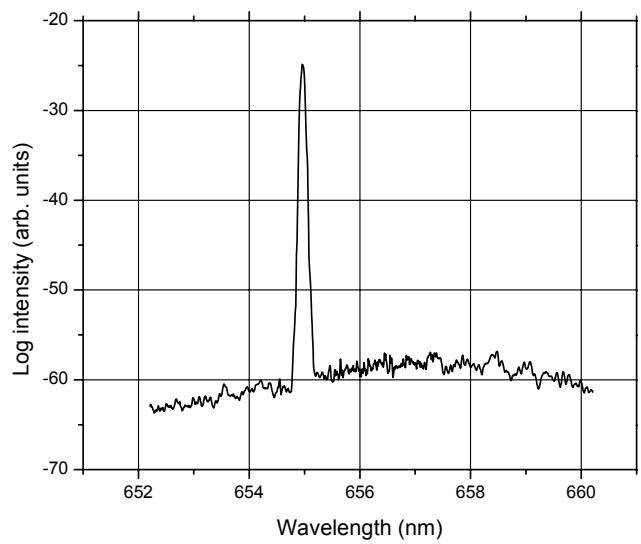
Flip Chip bonding of laser Gain chip with the PLC Micromachined Bench



Laser Ridge waveguide
Gain Chip

Waveguide
Grating Section

Light-Current Curve of the Hybrid Laser



Optical spectrum of 650-nm hybrid laser

Summary



InP/InGaAsP/InGaAsP-based Corrugated Pitch Modulated (CPM) DFB ridge-waveguide lasers with optical power >10 mW at ambient temperature with line width <300 kHz in 1.5-1.6 μm wavelength range has been demonstrated.

narrower linewidths should be possible for optimized laser cavities

CPM-DFB technology successfully extended to 2.05 μm wavelength region. Single mode operation with optical powers >10 mW has been demonstrated in devices fabricated from compressively strained multi-quantum well InGaAs/InGaAsP/InP laser structures.

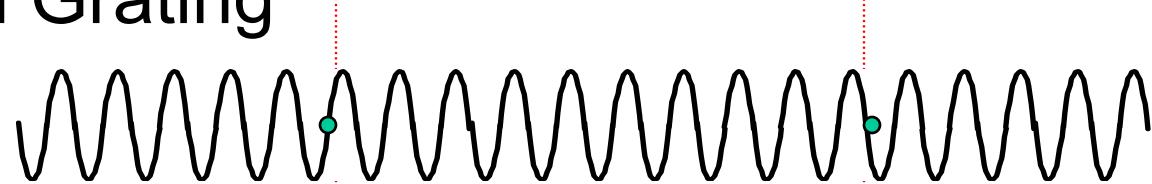
Linewidth yet to be determined, higher optical power should be possible.

High power ridge waveguide Fabry Perot lasers at 2.05 μm has been developed in InGaAsSb/AlGaAsSb/GaSb multiple quantum well laser structures.

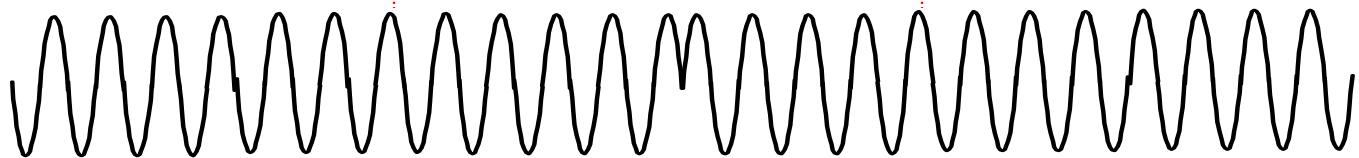
**Optical power >50 mW multimode (single element FP cavity)
Epitaxial material growth carried out by MIT-Lincoln Laboratory**

Hybridized external distributed Bragg reflector (DBR) waveguide grating lasers are very promising for spectral range shorter than 1.2 μm and greater than 2 μm .

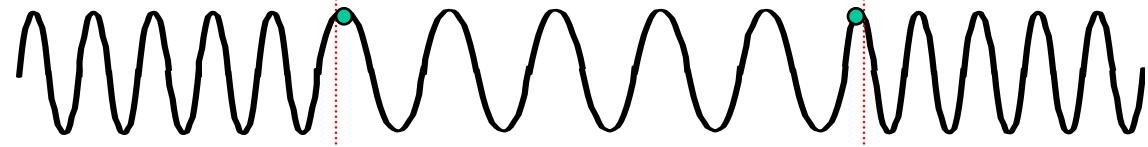
Uniform Grating



$\lambda/4$ -shifted grating



CPM grating



Phase-arranging
region

